

An embedded measurement system for electrical characterization of EGFET as pH sensor

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This work presents the development of an electronic system for the electrical characterization of pH sensors based on the extended gate field effect transistor (EGFET). We designed an electronic circuit with a microcontroller (PIC15F14K50) as the main component in order to provide two programmable outputs voltage as well as circuits to measure electric current and voltages. The instrument performance analyze was carried out using a glass electrode as a sensitive membrane for investigating the EGFET operation as pH sensor. The results show that the system is an alternative to commercial equipment for the electrical characterization of sensors based on field effect devices. In addition, some of the key features expected of this electronic module are: low cost, flexibility, portability and communication with a personal computer using a USB port.

Keywords: pH sensor, EGFET, field-effect device, microcontroller

I. INTRODUCTION

The ion-sensitive field effect transistor (ISFET) was presented by Bergveld at the University of Twente in 1968 as the first chemical sensor using a small semiconductor device [1]. At about the same time, but a little later, Matsuo from Tohoku University in Japan, after returning from vacation in Stanford, published his results showing a new type of device similar to ISFET, first in a Japanese journal, and later, in an international journal [2–4]. Over the years different applications using the ISFET were performed [4, 5]. For example, in 1983, J Van De Spiegel et al. reported the operation of the first extended gate field effect transistor (EGFET) based on the same ISFET operation principle except that the gate is not made directly in the MOSFET structure. It was first proposed as an alternative to the ISFET to detect at the same time in a single device multiple substances [6]. After 17 years, Li-Te Yin and colleagues presented to the scientific community a new alternative to EGFET manufacturing. Unlike J Van Der Spiegel, they developed the EGFET from the connection between a membrane sensitive to hydrogen ions and a commercial MOSFET (CD4007UB) [7, 8]. After these works other articles have been published exploiting both the optimization of the pH sensor devices as well as applications involving biosensors [9–15]. On the other hand, it is also relevant to highlight some efforts directed toward the development of scientific instruments related to research and technological development involving these devices [16–22]. Within this perspective, this work has as main objective to design and build up a dedicated electronic module for the electrical characterization of EGFET as pH sensor. Generally speaking, the procedures used to perform electrical characterization EGFET as a pH sensor have been similar to those used to obtain the characteristic curves

of the MOSFET except that in the case of EGFET the current is investigated as a function of the concentration of hydrogen ions present in the solution in which the membrane is immersed as shown in figure 1-a. So, in a nutshell, the measurement system must be capable of applying voltages to the MOSFET and the reference electrode while the current between the drain and source is monitored in such way that the value of these voltages as well as the current measurements must be remotely controlled by a personal computer allowing automation of experiments. Some of the key features expected of this electronic module are: low cost, flexibility, portability and communication with a personal computer using a USB port.

This paper is organized as follows: In the second section we present an overview of both the hardware, consisting of analog and digital circuits, as well as the programs developed in C language. Then in the third section, the results will be discussed with the object of analyzing system performance when it is used for the electrical characterization of EGFET as pH sensor considering a glass electrode as a selective membrane. Finally, we will present the conclusions and future prospects.

II. DESIGN AND DEVELOPMENT

Figure 1-b shows the block diagrams for the measurement system. There is a digital-to-analog converter (DAC) connected to a voltage follower to be used as a programmable voltage source. For each voltage source is present a block dedicated to the voltmeter and ammeter whose outputs are multiplexed to an analog-to-digital converter (ADC) in the microcontroller via the programmable gain amplifier (PGA) of six inputs. Communication between the microcontroller and the peripherals is performed by the SPI protocol, whereas with the personal computer through a USB port. Figure 2-A presents the schematic diagram for a programmable voltage source with two outputs based on the MCP4822.

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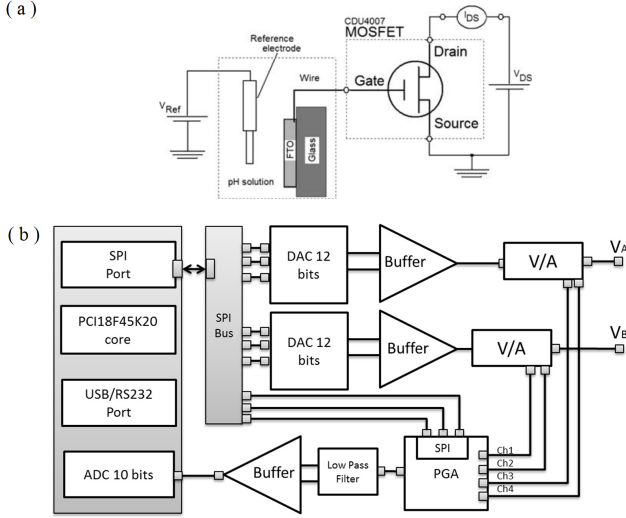


FIG. 1. (a) The EGFET as pH sensor consists of a sensitive membrane connected to a commercial MOSFET and a reference electrode. (b) The block diagram of the electronic module based on the microcontroller PIC18F45K20. It provides two programmable voltage outputs, voltmeters and ammeters.

Coupled to each output of this circuit is a voltage follower using the LM358 operational amplifier. The MCP4822 device is a DAC containing two outputs with 12-bit resolution and a serial communication according to the SPI protocol. Each of the two channels can operate in active mode or off according to the values present in the configuration registers. Then, the outputs A and B are monitored by the voltmeter as well as made available to the EGFET polarization with a resolution of 1 mV. As shown in figure 2-b, the electronic module uses a transimpedance circuit followed by a unit gain amplifier based on the TL082 (operational amplifiers with high input impedance) to perform the current measurement. This circuit has as main feature the conversion of low values of current in a voltage. It is distinguished by low sensitivity to parasitic capacitance of the circuit as well as effective control of the feedback circuit stability [23]. A feedback resistor provides a gain in the current-voltage relationship of 1:1000, i.e., a current of 1 mA at the input ammeter provides at the output a voltage of 1V. As the non-inverting input is grounded, the current values will then be perceived by the inverting input, and thus appear in the output voltage with reverse polarity. Therefore, a second amplifier is used to provide both the polarity inversion and the impedance matching between the ammeter and the next stage. Figure 3-a shows the electrical schematic of the data acquisition system that has as main component a microcontroller PIC18F14K50. Although the microcontroller has multiple ADC inputs with 10 bits of resolution, we use the PGA to maintain flexibility. In the future, this will allow using an external ADC of 12 bits. Furthermore,

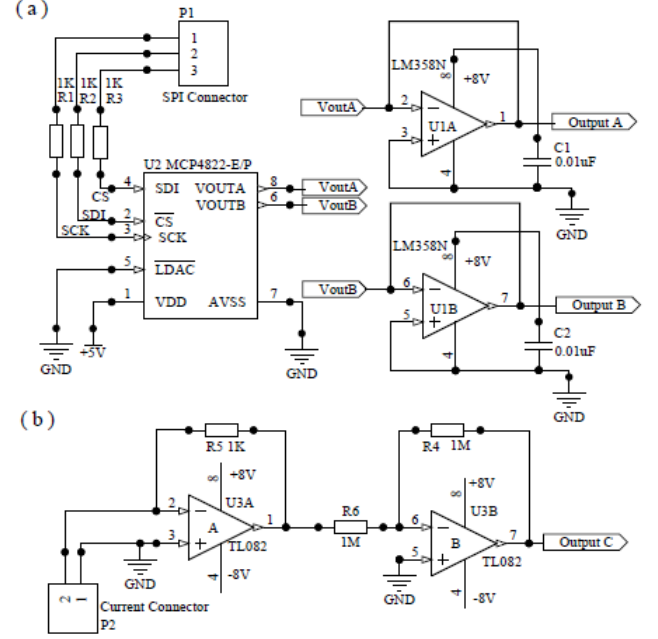


FIG. 2. (a) Programmable voltage source electrical schematic based on the MCP4822. (b) Transimpedance circuit used to convert the electrical current between the source and drain of the MOSFET into a voltage.

MP6S26 is capable of multiplexing up to six input channels with a gain of +1 V/V to +32 V/V. A standard SPI serial interface is used for receiving instructions from a controller. On output, the signal is fed to analogue-to-digital converter via a Sallen Key low-pass with a cutoff frequency of 10 Hz [24]. The ADC reference voltage is provided by the integrated circuit MCP1541, so that a voltage of 4.096V provides an ADC resolution of 4 mV. The MCP1541 input voltage is connected to the V_{IN} input device in parallel with the ceramic capacitor in order to reject the input capacitor noise voltage in the range of approximately 1 to 2 MHz. Noise above 2 MHz are well beyond the bandwidth of the reference voltage, and hence will not be transmitted from the input pin to the output. The load capacitance is required to stabilize the reference voltage. Finally, a converter RS-232 to USB was developed in order to provide greater flexibility using a PIC18F14K50 microcontroller as shown in figure 3-b.

To put into operation this instrument is still necessary to develop two programs, one for the microcontroller and one for the computer. The main idea is that using the application we can access all the peripherals connected to the microcontroller. In other words, at this point the microcontroller can be thought simply as a bridge between the personal computer and the peripherals connected to the microcontroller. This architecture is being proposed such that to achieve a great flexibility in the use of the hardware, taking into account only the specific needs of each application. Using this application it is possible,

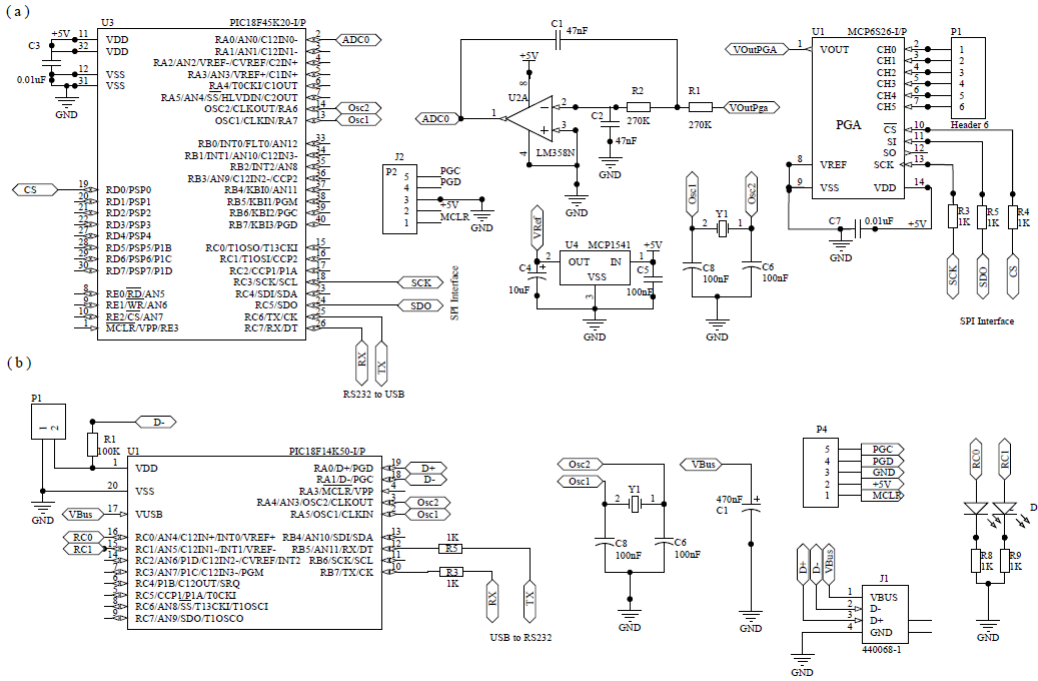


FIG. 3. (a) Data acquisition system built with the microcontroller PIC18F14K50 wherein the ADC input is connected to a programmable gain operational amplifier MCP6S26 through a Sallen Key low-pass filter. (b) USB-RS232 converter electrical schematic using a PIC18F14K50.

for instance, set the voltages on channels 1 and 2 as well as perform measurements of current and voltages across the ammeter and voltmeter in this module. In the first version, the program allows to select the initial and final voltage as well as the increment voltage for each channel. It is also possible to select how these values are varied over time. A trivial way is that the two sources are adjusted at the same time, being one of the sources may or may not remain at a value constant. At first the program has been developed to be run on the Windows operating system. However, the same source code can be easily adapted to other operating system. The complete code for both programs as well as the electrical schematic can be downloaded at no charge at the following electronic address: <http://batistapd.com>.

III. RESULTS AND DISCUSSION

In this first analysis, the electronic module performance was investigated considering the operation of the voltmeter and ammeter. Different calibration curves were obtained at the output of the MCP4822 using an Agilent digital multimeter connected to a personal computer via the USB port. The voltage is adjusted via the SPI port between 0 and 4.095 V at intervals of 0.5 V. Furthermore, when the microcontroller receives a command to read data, it performs the acquisition and conversion of the analog signal on the input of the ADC and then sends the results to the computer. The results,

not shown here, demonstrated that the electronic module maintains the voltage set by the program over time confirming that the voltmeter can be used to monitor the outputs present in the programmable voltage source efficiently. Likewise, to test the ammeter performance different resistors were used as current loads and based on the results we observe that the measuring current is satisfactory as expected, and thus, the ammeter can also be used to obtain the sensor curves. In the next

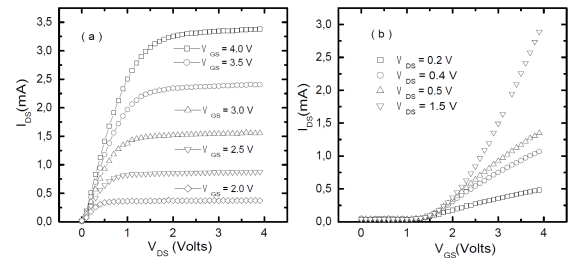


FIG. 4. Electrical characterization of CD4007B. (a) I_{DS} versus V_{DS} to different values of V_{GS} . (b) I_{DS} versus V_{GS} for different values of V_{DS} .

step, as an application, this electronic module is used for the CD4007B electrical characterization to determine the best condition for its operation as transducer. Figure 4-a shows the source-drain current (I_{DS}) as a function of the drain-source voltage (V_{DS}) for different values of gate voltages (V_{GS}). Note that the presence of a saturation current whose amplitude is related to the gate voltage.

The higher the value of V_{GS} , the larger the value of I_{DS} is. Figure 4-b shows the I_{DS} versus V_{GS} curves for different values of V_{DS} . For low values of V_{DS} , i.e., $V_{DS} < 0.3$ V, the MOSFET operates in the linear (Ohmic) region and the resistance is function of V_{DS} . These data are important to compute the device threshold voltage (about 1.5 V) as well as the EGFET sensitivity.

As a criterion for comparison, the EGFET operation as pH sensor is investigated using this measure system taking into account a glass electrode connected to the gate of the CD4007 as well as an electrolyte buffers of known pH, more specifically $H_2SO_4/NaOH$ based solution with their pH value ranging between 2 and 12. This electrode is adapted to EGFET to evaluate the electronic module performance because the sensor has a sensitivity of 55 mV/pH in a range of 2 to 12. The wire related to pH signal is connected to the gate of the MOSFET, while the other connection (ground or reference voltage) remains disconnected from the circuit. To complete the measurement system the reference electrode is also immersed in the solution. In this case, the voltage previously applied to the gate is now applied to the reference electrode (V_{REF}). Figure 5-a shows the EGFET charac-

I_{DS} depends on the pH value of the solution. Inasmuch as the pH varies from 2 to 12 the I_{DS} decreases from 1.25 to 0.6 mA. From these results, we can observe a linear relation between the square root of I_{DS} and the pH values as shown in figure 5-b. Figure 5-c corresponds to the experiment wherein the current I_{DS} is measured with V_{DS} constant in such way that the value of the EGFET sensitivity can be determined. Note that, the current curves shift to the right as pH value varies from 2 to 12. It can be obtained plotting V_{REF} as a function of pH for a current of 0.3 mA as shown in figure 5-d.

IV. CONCLUSION

We design a low-cost easy-to-make electronic module to investigate the operation of the EGFET as a pH sensor. The sensor consists of nothing more, nothing less than a membrane sensitive to hydrogen ions attached to the gate of a commercial MOSFET. Considering that the EGFET can be characterized electrically using the MOSFET traditional curves, the electronic module uses the PIC18F45K50 as a main component to provide two-channel programmable voltage as well as current and voltage meters. These peripherals are accessed by a program running on a personal computer via a USB communication in order to investigate the EGFET operation considering a glass electrode as a sensitive membrane. From the results presented, we can conclude that this measurement system is capable of generating a stable output voltage between 0 and 4.095 V. Finally, it was possible to show that the module obtains satisfactory way of characteristic curves EGFET functioning as the pH sensor. In addition to this feature, we are able to point out that the instrument developed could also be an alternative to the ISFET electrical characterization as well as other types of sensors based on the field effect transistor. Eventually, this module will be coupled to a system for heating and temperature control of the solution, thus allowing a study of the influence of temperature on the operation of sensors.

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V. REFERENCES

FIG. 5. EGFET electrical characterization using a glass electrode connected to the gate of CD4007B. (a) I_{DS} versus V_{DS} to different pH value fixing V_{REF} equal to 2.5 V. (b) Square root of I_{DS} as a function of pH value to V_{DS} equal to 2 V. (c) I_{DS} versus V_{REF} as a function of pH value considering V_{DS} equal to 0.2 V. (d) EGFET sensitivity curve computed using I_{DS} equal to 0.30 mA.

teristic curve considering the glass electrode immersed in solution with different pH values. The current is measured by fixing V_{REF} equals to 2.5 V. At the same time, V_{DS} ranges from 0 to 4 V at intervals of 100 mV. The

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VI. BIOGRAPHIES

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